<table>
<thead>
<tr>
<th>Proposal number:</th>
<th>2020-02</th>
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<tbody>
<tr>
<td>Proposal title:</td>
<td>Creating Sustainability-focused Value through Industrialized Construction: The Role of Organization-related, Process-related, or Product-related Strategies and Technology Interventions</td>
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</table>
| Principal investigator(s)\(^1\) and department(s): | Michael Lepech, Civil and Environmental Engineering  
Erica Plambeck, Graduate School of Business |
| Research staff:       | Michael Lepech, Erica Plambeck, Tess Hegarty (Stanford)  
Joe Louis (Oregon State University)  
Ankur Podder (US DOE National Renewable Energy Laboratory) |
| Total funds requested: | $100,000 |
| Project URL for continuation proposals | NA |
| Broad Category Addressed in this Research\(^2\) | energy & resource use / fosters business & economy |
| Project focus area addressed by proposal\(^3\) | Vision for the Future of Building Users / Design for Fabrication |
| Stakeholders’ benefitted by the research\(^4\) | Owners, Builders, and Operators/Facility Managers |
| Expected time horizon to impact the industry | 2 to 5 years |
| Type of research\(^5\) | Exploitation |
| Industry Involvement | US DOE National Renewable Energy Laboratory, Goldbeck (CIFE member), Prescient, Project Frog, Volumetric Building Companies, Skender, Inc., FullStack Modular, Factory_OS, Blokable |

\(^1\) The PI(s) must be academic council member(s) at Stanford.

\(^2\) Remove the categories that do not apply to this research proposal.

\(^3\) Remove the focus areas that do not apply to this research proposal.

\(^4\) Remove stakeholders that you do not anticipate to primarily benefit from this research.

\(^5\) Exploitation - “refinement, choice, production, efficiency, selection, implementation, and execution;”

Exploration - “search, variation, risk taking, experimentation, play, flexibility, discovery, innovation.” For more information please take a look at the following [article](#).
<table>
<thead>
<tr>
<th>Abstract (up to 150 words)</th>
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<tr>
<td><strong>Observed Problem, Primary Research Objective, and Solution:</strong></td>
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<td>Industrialized construction (IC) is proposed to improve construction sustainability. But is IC “more sustainable” because of better manufacturing processes or life cycle thinking? This research answers whether IC is more sustainable due to (i) improved organization/process control or (ii) improved product design/analysis.</td>
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<td><strong>Anticipated Value to CIFE Members and Industry:</strong></td>
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<tr>
<td>Construction firms create value throughout the value chain and eliminate non-value-adding activities to engage in modern “Activity-based Management,” or “ABM.” By identifying the sources of sustainability-focused value, this research enables ABM approaches for construction.</td>
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<td><strong>Proposed Research Approach and Methodology:</strong></td>
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<td>IC represents a continuum of industrialization from low (precast concrete) to high (unitary material logic). Working with partners, the sustainability-focused value of advanced modeling (digital twinning) and VR for IC will be quantified and associated with (i) improved organization/process control or (ii) improved product design/analysis within CIFE’s Product-Organization-Process framework.</td>
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<td><strong>Anticipated Research and Theoretical Contributions:</strong></td>
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<tr>
<td>Contributions: Research - (i) understanding sustainability-focused value-creation, (ii) ABM framework for IC. Theoretical - (i) extending the POP framework, (ii) linking POP with ABM theory.</td>
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1 https://www.nrel.gov/buildings/industrialized-construction.html
1 Engineering or Business Problem

Industrialized construction (IC) techniques are being leveraged to improve the efficiency and sustainability of the built environment. IC companies frequently claim improved sustainability relative to traditional approaches as a key value proposition. On the company level, questions about the effectiveness of various pathways toward cost-effective sustainability enhancements should be informed by life-cycle sustainability metrics. The degree to which structural markers of industrialized construction (Lessing, 2006) truly deliver improved sustainability metrics needs to be established so that the effectiveness of continuous improvement efforts (Meiling, Backlund, & Johnsson, 2012) can be maximized.

An improved sustainability profile is one of the key value propositions of IC; however, the foundational mechanisms or pathways by which these structural features of IC contribute to improved sustainability and other value propositions (McKinsey, 2017) (Lessing & Brege, 2015) remain unclear, as shown in Figure 1. We want to know if industrialized construction is “more sustainable” due to better process control (i.e., reducing variation and defects of all types) or due to the application of more comprehensive, life-cycle concepts in product design and modeling (i.e., reducing the average building footprint)?

This research looks to answer fundamental questions regarding the sustainability-focused value proposition of industrialized construction: to what extent does industrialized construction (IC) achieve its sustainability value proposition due to (i) improved organization and process control vs (ii) improved product design and analysis techniques?

Of the structural aspects shown in Figure 1, we are seeking to understand the intersection of off-site prefabrication of building parts with increased use of information and communication technology (ICT), as shown in Figure 2. Strategic ICT integration is thought to enhance value of offsite production systems in industrialized construction (Malmgren, Jensen, & Olofsson, 2011). Specifically, this research will focus on the role of discrete event simulation (DES) of the real-world prefabrication process and visualization of the results via digital twins in virtual reality.
(VR) simulation to drive either organization/process-related improvements or product-related sustainability improvements in industrialized construction. The application of rigorous sustainability quantification tools and the linking with management techniques will provide a framework for practical application of these findings.

2  Theoretical and Practical Points of Departure

2.1 Prefabrication Process Simulation
Simulation allows us to model real systems and gain insights about their performance. It is a “preferred means for studying systems, especially when it is expensive or infeasible to obtain insights from the real system under study through real-world experimentations.” Discrete event simulation (DES) using jStrobe simulation software, can be used to simulate construction operation alternatives and select the effective option (Abiri, Louis, & Riggio, 2019).

Sensors placed in the factory collect data on the environment to inform the DES. These sensors capture vibrations, audio, movements, and video (Louis, 2020). The use of DES has been proven to help quantify savings in lead time, material use, and cost due to a continuous improvement intervention in an industrialized construction process. DES data has been integrated into a digital twin which exists for the production of volumetric wood-framed modules in a factory of an IC company (Volumetric Building Companies) as shown in Figure 3. By “digital twin”, we are referring to a virtual reality model of a real production line in an industrialized construction factory that integrates data from discrete-event simulation. Sensors in the factory keep the digital twin updated to current factory conditions.

Factory productivity is determined by the interaction of equipment, labor, space, and materials, which are all factors that the digital twin captures. Digital twins can be leveraged to enable continuous improvements in the production process, identify bottlenecks, and ensure that interventions are working as planned. The digital twin can also be used to forecast performance and what-if scenarios, enabling the optimization of resource allocation.

2.2 Probabilistic Life Cycle Assessment
Life Cycle Assessment (LCA) is “a tool for quantifying the environmental performance of products taking into account the complete life cycle” starting from raw material production to the final disposal or recycling of the products (Goedkoop, Oele, Leijting, Ponsioen, & Meijer, 2013). The vast majority of LCA is done deterministically, based on average inputs, which makes the results seem more precise and certain than they are. As shown in Figure 4, this can mislead decisions intended to improve sustainability (Lepech, Geiker, & Stang, 2014; Pomponi, D’Amico, & Moncaster, 2017).
Probabilistic LCA can be performed in Excel based on a SIPMath Monte Carlo simulation approach. SIPMath probabilistic modeling performs computations using Stochastic Information Packets (SIPs), in which uncertainty is modeled as an array of possible outcomes (ProbabilityManagement, 2018; Savage & Thibault, 2014). Using SIPMath, uncertainties are represented as thousands of possible outcomes within an array, this preprocessing of uncertain outcomes enables rapid probabilistic analysis of many uncertain variables simultaneously in the native Excel environment.

2.3 Process, Organization, Product (POP) Framework

The Product, Organization, Product (POP) framework was developed at CIFE to enable the application of design thinking in building design with the goal of realizing highly valuable buildings (Fischer, Ashcraft, Reed, & Khanzode, 2017). Highly valuable buildings are useable, buildable, operable, and sustainable. Function and form are connected with predicted and observed performance (behavior) across three design levers (product, organization, and process).

2.4 Activity-based Management Model

In cost-competitive industries like construction, it is imperative that firms understand the creation of customer value throughout the value chain, and eliminate non-value adding activities that incur costs but provide no value to the end customer (Lanen, Anderson, & Maher, 2020). Activity-based management (ABM) systems examine processes and activities to determine their effects on costs (Anderson, 1993; Gupta & Galloway, 2003). An ABM system can enable analysis of the “activities in terms of product and process design features, and thereby provides valuable information to the product designers by supplying the cost implications of alternative design choices”. The system can identify factors under the control of design engineers that influence manufacturing costs. Without such systems, companies tend to “design more complex products because the price and market share advantages are perceived to outweigh the additional costs of designing, manufacturing and supporting complex products” (Gupta & Galloway, 2003).

3 Research Methods and Work Plan

3.1 Research Context

A number of proposed industrialized construction technologies have been identified that represent a continuum of industrialization, a few of which are shown in Figure 5. This continuum ranges from very low levels of industrialization (e.g., precast concrete elements) to very high levels of industrialization (e.g., unitary material logic of CARBONHOUSE in which a single material is used to produce all parts of the built environment). Volumetric modular and kit-of-part approaches with varying degrees of predefinition fill out the space between these extremes.

This research proposal focuses on (i) continuous improvement activities for VBC’s volumetric modular, wood-framed approach, as well as (ii) comparing the industrialized construction approach with a functionally equivalent traditional construction approach.

![Figure 4: Probabilistic LCA increases the likelihood of meeting sustainability targets (Pomponi et al., 2017)](image-url)
3.2 Case Study 1: improved IC approach vs baseline approach

This case study is rooted in work by collaborators Louis and Podder (NREL) and VBC, as explained in 2.1. It is focused on “continuous improvements” in the IC approach. This methodology is also available in visual format in the Appendix.

First, we will identify and quantify the differences between the IC approach vs the baseline approach using integrated DES data. Next, we will quantify the sustainability of both approaches by developing a spreadsheet-based probabilistic LCA of a volumetric modular unit (using SIPMath in Excel) informed by DES data and the ecoinvent database in SimaPro (Goedkoop et al., 2013). This part of the methodology will be building off existing work linking DES & LCA, as shown in Figure 6 (Feng, Lu, Chen, & Wang, 2018; Mawson & Hughes, 2019). Then the differences identified will be related to the POP framework, categorizing them as product, organization, or process changes and using sustainability impact metrics, such as CO2-equivalents, to add quantification to the framework. Next, the results will be related to activity-based management, to help answer questions such as, “Are improvements in IC delivering on a sustainability value proposition?” Finally, we will update the digital twin with DES and LCA results, so that the digital twin virtually reality environment can be used to identify potential improvements and rapidly update DES/LCA results to explore continuous improvements.

3.3 Case study 2: IC approach vs traditional construction

Case study 2 builds off of case study 1 to look at how the IC approach compares to a traditional construction site build with respect to a building-scale sustainability value proposition. The DES data from case study 1 will provide inputs for the LCA of the IC approach. Our collaborators will set up sensors and the DES on a traditional construction site in order to allow us to identify and quantify differences between IC approach vs traditional construction approach. The methodology will be similar to that explained above (and is available in visual format in the Appendix), but without integrating the information into a digital twin. If no real-world traditional construction project as a baseline for comparison can be identified, DOE reference buildings for use in
building energy modelling are available, and can be modified to provide a functionally matched comparison. The probabilistic LCA results coupled with the POP framework will allow us to classify and quantify the life-cycle sustainability advantages of IC approach has in comparison to the traditional construction approach.

4 Expected Results: Findings, Contributions, and Impact on Practice

4.1 Expected Practical and Theoretical Contributions

A number of practical research and theoretical contributions are expected from this research effort. Expected practical research contributions include: (i) a deeper understanding of the mechanisms behind creation of sustainability-focused value in the industrialized construction industry, (ii) a framework for engaging in Activity-based Management in the sustainability-focused value chain of industrialized construction, and (iii) refinement of fundamental holistic sustainability research tools (probabilistic LCA spreadsheets). Expected theoretical contributions include: (i) extension of the Product-Organization-Process framework to include quantitative measures of value creation, with a focus on sustainability and (ii) theoretical linking between the Product-Organization-Process framework and the management theory of Activity-based Management.

4.2 Expected Impact on Practice

The research proposed in this project is part of our larger goal of elevating the reliability, rigor, uptake, and impact of sustainability quantification within the AEC industry, such that stakeholders are empowered to achieve triple-bottom line sustainability goals (Lepech et al., 2014). Discrete-event simulation of off-site construction processes will inform more detailed probabilistic LCA of finished IC products.

We expect this research to help building owners better define sustainability goals for the POP framework and enable the IC industry to meet these goals in a cost-effective manner. Specifically, the framework for engaging in Activity-based Management in the sustainability-focused value chain of industrialized construction will help industry partners predict which sustainability interventions will be simultaneously cost effective and achieve their targeted sustainability goals. We plan to present findings at the CIFE IC Forum in 2022, and expect this research to impact the industry within five years.

Probabilistic LCA spreadsheet models providing rapid feedback on potential changes will be useful to the industry as a foundational holistic tool to inform management and design decisions. This work will also be of practical use to those IC companies with a software focus (e.g. Project Frog and Prescient), especially as we work in the future to develop these probabilistic LCA spreadsheet tools into versions that can be integrated into BIM/BEM workflows via Grasshopper or Dynamo (Cavalliere, Habert, Dell’Osso, & Hollberg, 2019). We hope that future collaboration with such companies can enable widespread adoption of probabilistic LCA in the IC landscape.

5 Industry Involvement

Volumetric Building Companies has been collaborating with NREL and research collaborator Louis on a discrete-event simulation case study project (Louis, 2020) that is part of NREL’s ongoing research effort: “Integrating Energy Efficiency Strategies and Distributed Energy Resources into Industrialized Construction” (NREL, 2020). This case study will be a point of departure for the case studies of this project. NREL has additional industry partners, especially
Factory_OS (as well as Skender Inc., FullStack Modular, and Blokable) that are candidates for future additional case studies.

The proposal team is currently looking for CIFE members on the AEC industry side as potential candidates for similar future collaborations. Discussions are underway with DPR on the contractor side, as are members on the owner-operator side, such as Gilead. CIFE member Goldbeck is currently beginning collaboration on similar research with researcher T Hegarty.

6 Research Milestones and Risks

6.1 Research Milestones

M1 – Identify two relevant IC case studies with research collaborators (case studies already underway, travel funding requested to visit traditional construction site to observe and measure traditional construction baseline for second case study along with research collaborators)

M2 – Identify specific changes relative to the baseline or traditional construction approach, connect two case studies to POP framework, and collect DES data (DES data already available, except for traditional construction approach)

M3 – Complete probabilistic LCA of both case studies, using DES data to inform input distributions, and integrate quantification into POP framework

M4 – Connect LCA findings to management theory, creating an activity-based management framework for IC

M5 – Present findings and host panel at CIFE IC Forum 2022 or host workshop to share research findings (funding requested to bring research collaborators to campus)

6.2 Research Risks

R1 – Difficulty identifying traditional construction comparison for case study 2 and setting up discrete-event simulation for the traditional approach (minimal risk due to number of potential industry partners including CIFE members and existing connections of other research collaborators, as well as backup use of DOE reference building models to simulate traditional construction approach)

R2 – Unable to quantify means and standard deviations of manufacturing process statistics (minimal risk because collaborators already have been able to model the factory process via DES and will be able to simulate various scenarios virtually via a digital twin)

R3 – Unable to quantify means and standard deviations for inputs to probabilistic LCA (moderate risk, may be gaps in data making it difficult to quantify all LCA inputs probabilistically, in which case may only quantify standard deviations for key inputs and/or may use Pedigree matrix to estimate uncertainties (Goedkoop et al., 2013)).

7 Next Steps

ARPA-E has awarded $3.7 million in funding to MIT’s CARBONHOUSE project (ARPA-E, 2018), and Stanford’s Precourt Institute for Energy has granted seed funding to P.I. Lepech for developing probabilistic LCA tools for the CARBONHOUSE project, indicating ongoing interest in funding research on sustainability of IC approaches. Stanford’s Precourt Institute has recently announced its “Decarbonizing Buildings” initiative; this is a potential source of follow on funding for similar research understanding the pathways linking structural markers of IC and the sustainability value proposition of IC. Follow on funding will be sought with a joint proposal with NREL to the DOE, as well as a proposal to ARPA-E.
8 References


GOLDBECK. (n.d.). Retrieved from https://www.goldbeck.de/


9 Appendix

Case Study 1 Continuous improvements in IC?

Improved pre-insulated studs integrated in factory

VS

Baseline continuous insulation, added on-site

improved IC approach compared to baseline IC approach

Case Study 2 Advantages of industrialized construction?

IC building compared to equivalent traditional construction building

Case Study 1 Continuous improvements in IC?

Baseline 
- DES results
- ecoinvent database

Improved 
- DES results
- LCA inputs ($\mu$ & $\sigma$)

Compare probabilistic LCA results
Are there changes in the mean ($\mu$) or standard deviation ($\sigma$)?

POP framework
Are they product differences or process/organization differences?

Activity-based management
Are the improvements delivering on the sustainability value proposition?

Update digital twin
Use digital twin to rapidly update DES/LCA to explore future improvements

DES results 
- LCA inputs ($\mu$ & $\sigma$)

Probabilistic LCA using SIME

Probabilistic LCA using SIME
Case Study 2
Advantages of IC vs traditional construction?

Traditional
- DES results
- Ecoinvent database

IC
- DES results
- LCA inputs ($\mu$ & $\sigma$)
  - LCA inputs ($\mu$ & $\sigma$)

Compare probabilistic LCA results
Are there changes in the mean ($\mu$) or standard deviation ($\sigma$)?

Identify & Quantify $\Delta$s
What are the differences between IC approach vs traditional construction approach?

POP framework
Are they product differences or process/organization differences?

Activity-based management
Are the improvements delivering on the sustainability value proposition?